Kwantificatie van de invloed van regen op de verkeerdoorstroming

Simeon C. Calvert
TNO & TU Delft
simeon.calvert@tno.nl

Wouter van Stralen
TU Delft
wouter_van_stralen@hotmail.com

Eric J. E. Molin
TU Delft
e.j.e.molin@tudelft.nl

Bijdrage aan het Colloquium Vervoersplanologisch Speurwerk
21 en 22 november 2013, Rotterdam

Samenvatting

Kwantificatie van de invloed van regen op de verkeerdoorstroming

Het is bekend dat het weer invloed heeft op het verkeer op snelwegen, en in het bijzonder filevorming. Op de eerste plaats wordt de wegcapaciteit tijdelijk beinvloed door een verandering in rijgedrag van bestuurders. Ten tweede beinvloed het weer ook de verkeersvraag. Vertragingen op het Nederlandse hoofdwegennet leiden tot aanzienlijk economische schade. Vertragingen werden tussen mei 2010 en april 2011 geschat op 68 mijoen veortuigverliesuren. Door de ontwikkeling van een generieke model, kunnen de kansen op specifieke verkeersvragen en capaciteiten worden berekend. Hiervoor isgebruik gemaakt van een *stated adaption experiment in* combiatie met een *Panel Mixed Logit* model om de verschuivingen in de verkeersvraag in kaart te brengen. Verschuivingen in de wegcapaciteit zijn uitgevoerd door extesieve data analyse, waarbij het *Product Limit Methode* toegepast is op uiteenlopende weerssituaties. Het is aangetoond dat neerslag in de vorm van regen een significante verandering in de kans op filevorming veroorzaakt. Wanneer onder droge omstandigheden een kans op file aanwezig is van 50%, wordt dit 86.7% bij lichte regen, en 77.4% bij zware regen. De hogere filekans bij lichte regen ten opzichte van zware regen heeft vooral te maken met een verhoogte verkeersvraag. Met de ontwikkeld model kan elk willekeruge filekans worden berekend. Wij concluderen dat onder niet-reguliere weersomstandigehden het van belang is dat men rekening houdt met de veranderingen die op kunnen treden in de verkeersvraag en wegcapaciteit, en daarmee ook de kans op filevorming.

1. Introduction

Congestion effects on motorways lead to serious economic damage. For example, in the Netherlands there were 68 million vehicle loss hours as a result of congestion between May 2010 and April 2011 (TNO, 2011). The weather is widely acknowledged to contribute to the occurrence of congestion in two different ways. Firstly, weather conditions can influence the traffic supply through a temporal reduction of capacity resulting from drivers reducing their speed and allowing greater time headways. A well-known piece of literature into the effect of weather on traffic flow is presented in the Highway Capacity Manual (2000). The manual suggests capacity reduces by between 0% and 15% as a result of precipitation. Motorway capacity reduction is traditionally regarded as a deterministic phenomenon, but numerous researchers (Elefteriadou et al. 1995; Minderhoud et al. 1997; Persaud et al. 1998; Lorenz and Elefteriadou 2001, Brilon et al., 2005) have shown that the maximum capacity of a motorway varies even when the external factors are constant. This results from the unpredictable behaviour of drivers on the microscopic level. Motorway traffic demand is also influenced by weather conditions, while the effect of weather on traffic demand has received much less attention than the effect on motorway capacity according to Böcker et al. (2012). In their literature review, Böcker et al. show that many studies have found different effects of precipitation, temperature and wind on traffic demand. Call (2011), amongst others, reported considerable reductions in trip-making with snowfall. Car traffic reductions are also reported as a consequence of rainfall, for example by Hassan and Barker (1999) in Scotland. Where most studies show negative precipitation effects on trip generation, a Dutch study from Sabir (2011) shows a positive relationship between precipitation and car and public transport usage. This is the result of the large number of cyclists in the Netherlands, of which some switch to motorized transport modes in response to precipitation.

Surprisingly though, an explicit study towards the combined effect of changes in motorway capacity and motorway traffic demand as a result of the weather has not been carried out yet. This aim of this paper is to contribute to the literature by developing a method that includes both supply and demand aspects. This study focuses on the probability of traffic breakdown on Dutch motorways as a result of adverse weather conditions, including both motorway capacity reductions and traffic demand changes resulting from adverse weather. To estimate the effects of adverse weather on motorway traffic demand, a stated adaptation experiment is conducted. In this experiment, car drivers choose among a range of travel alternatives depending on the presented weather conditions. Based on the observed choices, a Panel Mixed Logit model is estimated of which the results are presented and interpreted in this paper. To examine the influence of precipitation on motorway capacity it was chosen to estimate capacity distribution functions based on the Product Limit Method. To get accurate predictions of the traffic demand change and have sufficient observations with congestion, it is chosen to limit this study to the morning peak period (between 6:00 and 10:00 am). As will be explained later, due to data limitations, functions could only be estimated for dry weather, light rain and heavy rain, and not for snowfall. With the development of a generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and capacity.

2. Methodology

In this section the relation between motorway morning peak traffic demand and motorway capacity is made explicit to provide insights into the possibility of linking both factors later in the analysis. For the capacity analysis, a stochastic approach for capacity is used based on the following definition of capacity: "the rate of flow along a uniform freeway segment corresponding to the expected probability of breakdown deemed acceptable under prevailing traffic and roadway conditions in a specific direction" (Lorenz & Elefteriadou, 2001). Applying the concept of stochasticity to the motorway capacity leads to a probability density function that provides the probability of breakdown given a certain traffic flow, for which an example is shown in Figure 1.

Figure 1 - Breakdown probability at motorway A4 in dry and heavy rain conditions

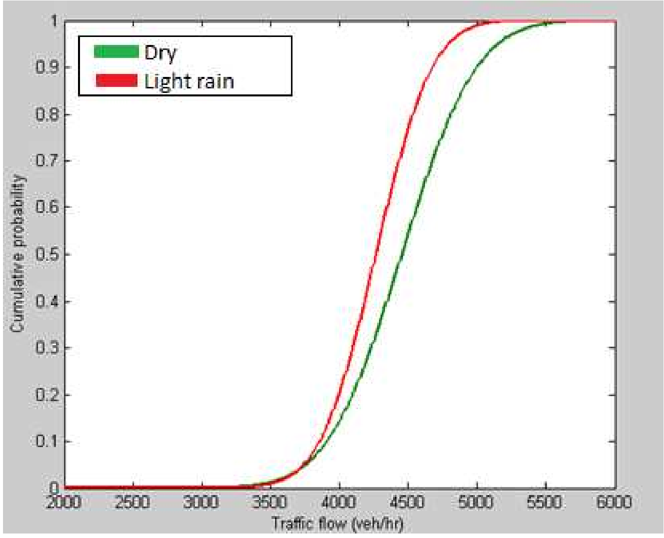

Figure 1 shows the capacity distribution function at motorway A4 in 2007 in dry weather conditions (bottom line) and in heavy rain weather conditions (top line). A comparison is made between the breakdown probability based on the estimated capacity distribution functions for scenarios with and without precipitation. The motorway travel demand, whether increasing or decreasing in these scenarios, also affects the breakdown probability. The link between motorway capacity and motorway traffic demand is thus based on the influence that both factors have on the probability of breakdown.

2.1 Capacity Analysis

2.1.1 Choice capacity estimation method

In this research, the Product Limit Method (PLM) by Kaplan and Meier (1958) with adaptations as described in Brilon et al. (2005), is used in the capacity analysis to come to a function describing the probability of breakdown. The PLM method as described by Brilon considers traffic flow observations upstream of a bottleneck location. Measurement upstream of a bottleneck location takes into account that the capacity in uncongested traffic flows differs from the capacity in congested conditions, which is the result of the so-called capacity drop phenomenon (Zurlinden, 2003; Regler, 2004; Chung et al., 2007). Consideration of only pre-breakdown traffic flows for capacity estimation is major difference to other PLM implementations, which also consider congested traffic flow observations (van Toorenburg, 1986; Minderhoud, 1997).

2.1.2 Bottleneck location detection

The capacity estimation method relies on the occurrence of many breakdowns to arrive at a reliable capacity distribution function based on a large dataset. Therefore, only static bottleneck locations with many congested morning peaks during the year are analysed in this research. The bottleneck locations are identified by analysing data from double-induction loops. Traffic data is collected from double-induction loops that are present on the Dutch motorway network, which is known as the MONICA system (Dutch MONItoring Casco). For each minute data is stored regarding the average speeds (km/h), flows (veh/min) and possible lane closure for all the motorways included in the MONICA system. For the capacity analysis in this study, data from the years 2007, 2008 and 2009 are inspected of various Dutch motorways (A2, A4, A6, A9, A15, A16, A20, A27, A50, A58 & A59). Three criteria are applied for static bottleneck locations to become suitable for analysis. Firstly, the induction loops at and around the bottleneck locations should work properly. Secondly, congestion at the bottleneck location should not be initialized by spillback from a bottleneck downstream. Thirdly, the bottleneck may not consist of a variable number of lanes over the day (for example peak hour lanes). In total fourteen bottleneck locations met all three requirements and were considered suitable for the capacity analysis.

2.1.3 Categorization of the traffic flow observations

To arrive at a capacity distribution function, the traffic flow observations are categorized into three different classes. Observation intervals of five minutes are used, since this gives a good compromise between reducing the random fluctuations in the traffic flow and accuracy in the average intensity values (see Brilon et al., 2007). Only observations within the morning peak period (6am-10am) are included in the analysis. Additionally, observations of weekend days and vacation periods are excluded. Each of the remaining five-minute traffic flow observations are placed into one of the following categories:

B: The traffic volume is as a realization of the capacity due to the fact that observed flow in this interval is uncongested, but causes a breakdown in the following interval i + 1. In this study, an average speed of 60 km/h is the applied as congestion threshold (Calvert & Snelder, 2013). An extra requirement for this observation is that during the preceding 6 observations (30 minutes) the average speeds were higher than 60 km/h. This is added to ensure uncongested flow before the occurrence of breakdown.

F: The traffic flow is uncongested in interval i and in interval i + 1. The information obtained from this observation shows that the actual capacity in interval i may be greater than the volume qi that is observed. This censored data is valuable to a correct quantification of the breakdown probability.

C: The traffic flow is congested in interval i and in interval i – 1, thus the average speed in both intervals is lower than the threshold value. Since the traffic volume in interval i – 1 also congested, the observation does not provide information about the free flow capacity and is therefore excluded from the free flow capacity analysis.

After the observations are grouped into the different categories, rain data is added to these observations. The rain data is collected from a data feed of the Royal Netherlands Meteorological Institute. The rain data feed provides data for a grid with the size of 1km by 1 km for the Netherlands on a one-minute basis. The rain detection and intensity estimation is performed via advanced satellite images and has realized excellent accuracy during the latest years. The one-minute rain intensity data is averaged to five-minute intervals and these intervals are mapped onto the road network with latitudinal and longitudinal coordinates (Calvert & Snelder, 2013).

2.1.4 Capacity distribution function estimation

The classified and filtered traffic observation intervals possess information regarding the average intensity and the average speed during that interval. With the information regarding the average speed, average intensity and the category of each observation interval, it is possible to estimate a distribution function for the free flow capacity using the Product Limit Method (PLM) by Kaplan and Meier (1958). This leads to a free flow capacity distribution function at the bottleneck that is estimated as follows:

$$F_c(q) = 1 - \prod_{i:qi \leq q} \frac{k_i - d_i}{k_i}; i \in \{B\}$$

Where:
$F_c(q)$ = capacity distribution function
q = traffic volume (veh/h)
q_i = traffic volume in interval i (veh/h)
k_i = number of intervals with a traffic volume of $q \geq qi$
d_i = number of breakdowns at a volume of qi
$\{B\}$ = set of breakdown intervals (intervals with classification B)

The calculation is made for each breakdown interval observation. Each observed breakdown is normally used as one q_i-value, which leads to d_i always being equal to 1. The factor k_i is based on all observations (thus B- and F-observations) with a traffic volume (q) that is higher than the traffic volume at the breakdown observation (q_i). The points at the capacity distribution are thus B-observations, but in order to arrive at the probability of that certain point the F-observations are also included into the estimation.

2.2 Stated adaptation experiment

In this section, the stated adaptation experiment is described that was conducted to estimate the extent traffic demand changes on Dutch motorways changes with adverse weather conditions. In this experiment, it is observed how respondents may adapt their travel behaviour under various hypothetical weather situations. For each of presented weather conditions they are requested to make a choice between the following six travel alternatives:

1. Travel by car on the motorway in the morning peak
2. Travel by car, but avoiding the morning peak (before 06:00 or after 10:00am)
3. Travel by car, but avoiding the motorway
4. Travel by bicycle
5. Travel by public transport
6. Decide not to make the trip

In the following, first the construction of the weather conditions is discussed. This is followed by the way trip purpose was included in this study. Then, the data gathering procedure is described. Finally, attention will be paid to the model estimation.

2.2.1 Selection of attributes

A first attribute that describes the weather conditions is *precipitation*, which reflects the current precipitation at the moment when the decision about a trip in the morning is made. This attribute consists of five levels, which are *dry weather*, *light rainfall*, *very heavy rainfall*, *light snowfall* and *heavy snowfall*. Pictures are included for each of the precipitation levels in order to make the terms light and heavy more tangible. This is done in order to mitigate effects due to different perceptions of precipitation conditions among the respondents.

The second attribute is the *weather alarm* that is sometimes issued by the Royal Netherlands Meteorological Institute in case of extreme weather conditions. A weather alarm with code red will be carried out at most twelve hours in advance if the probability of occurrence of the event is at least 90%. It is only used if the area that is confronted with the weather has at least a length of 50 kilometres (KNMI, 2011). The following alarms codes are varied in this experiment: *code red for heavy rainfall* (at least 75mm in 24 hours), *code red for snow* (at least 3cm per hour or 10cm per 6 hours) and *code red for icy roads*. The final level is the event of *no weather alarm*.

The third attribute is the *weather forecast*, which is included in the experiment as the weather forecast. Generally, forecasts provided by the news broadcasting do not provide very specific information regarding the weather during the coming day. Based on this notion rather general levels have been formulated for this attribute, that is, during the day the weather conditions can: *improve*, *get worse* or *stay the same* as the current weather conditions.

The selected attributes are combined by using an efficient design to arrive at the weather condition descriptions. Based on a pilot study with 30 respondents, priors were estimated that were used to arrive at the efficient design. To ensure that only logical weather combinations were constructed, several constraints were included. In total, 20 different weather situations were constructed. To limit the number of conditions shown to each respondent, the weather conditions were blocked into two groups of 10 conditions. Each respondent was presented only one the blocks of 10 weather conditions.

2.2.2 Trip purpose

Travel behaviour can vary with trip purpose. Those traveling for work related purposes may have more limited possibilities to adapt their travel plans than those traveling for recreational purposes. Two categories of trip purpose are therefore distinguished. The first category consists of business trips, commuter trips and educational trips, which we define as *utilitarian trips*. The second category consists of trips for visiting family or friends, grocery shopping, shopping, a day-out, going to sports etc, defined as *recreational trips*. For each of the presented weather conditions respondents are asked to indicate separately for utilitarian trips and for recreational trips their travel choice, provided they typically travel for this purpose in a normal workweek. The latter information is gathered in the first part of the questionnaire. Hence, this procedure allows us to estimate separate models for utilitarian and recreational trips.

2.2.3 Questionnaire and sample

The stated adaptation experiment was included in an online questionnaire and was preceded by socio-demographic characteristics and questions regarding the normal travel behaviour of the travellers regarding motorway use. To gain insight into normal travel behaviour, questions were asked regarding the number of utilitarian and recreational trips that are made in a normal workweek in the morning peak, the common for both purposes, the distance from home to work, the possibility to avoid the morning peak and the possibility to work at home. In collaboration with public survey panel, selected members were invited to fill out the survey. In total 342 respondents filled out the survey completely (response rate of 22%), of which 210 respondents only provided responses for utilitarian trips, 71 only for recreational trips and 61 respondents provided responses for both trip purposes. This resulted in 2710 observations for utilitarian trips and in 1320 observations for recreational trips.

2.2.4 Model estimation

Effects coding is applied to code the attribute levels, with the result that the constant estimated for each alternative denotes the average utility derived from that alternative. The estimated effects for each attribute levels then denote the extent to which utility of an alternative changes if that attribute level is present in the weather condition, which is expressed as deviations from the average utility. Effects coding resulted in four *current weather* indicator variables, two *weather forecast* and three *weather alarm* indicator variables. The coded attributes were included in the utility function of the alternatives and were all estimated alternative specific. It was expected that the choice for any of the alternatives largely depended on the current and therefore the favourite travel options during the morning peak hours. The following groups were distinguished based on mode and motorway use during morning peak hours: motorway car group, non-motorway car group, public transport group and cyclists. These groups were also effects coded and added to the utility function of each alternative. Hence, a significant effect estimated for these group indicators means that the utility this group derives from that alternative differs from the average utility across all groups.

The utility models were estimated in Biogeme (Bierlaire, BIOGEME: A free package for the estimation of discrete choice models, 2003), separately for utilitarian and recreational travel behaviour. A basic MNL model estimated for utilitarian trips including only the alternative specific weather condition attributes had a Log-Likelihood value of -3882.16 and a Rho-square value of 0.200. If the current travel option is added to the utility functions, the log-likelihood considerably increases to -2005.48 and the Rho-square becomes 0.587, confirming that as expected the current travel option plays a large role in the choices among the alternatives.

In addition, a panel mixed logit model is estimated to take the so called panel effect into account, that is, the 10 observed choices of each respondent are likely to be correlated as a result of the preferences of the respondent. More specifically, we assumed that the preferences for the alternative specific constants follow normal distributions and estimate a mean and a standard deviation for each alternative specific constant. This model is estimated by simulation by which error terms are drawn from a normal distribution, where a single error term for each individual is drawn for all the choices observed for that individual. This procedure results in more valid t-values as these are no longer based on the number of observations but on the number of respondents. Taking this panel effect into account further improved the Log-Likelihood towards 1386.50 and leads to a very high Rho-square value of 0.714. For the recreational trips, the basic MNL model has a LL values of -2085.69 and Rho-square value of 0.118. Including the current mode choice indicators increases the Log-likelihood towards -1846.74. The Panel Mixed Logit model also resulted in a significant improvement of the model (LL = -1348.86) and leads to a relatively high Rho-square value of 0.430. The presented models were estimated by applying 500 Halton draws.

3. Results

3.1 Capacity analysis

In this section the capacity in different weather scenarios is compared. The first scenario is the reference case of dry weather. Secondly, the effect of light rain on motorway capacity is investigated by only analysing traffic flow intervals with precipitation intensities between 0.01 and 1 millimetre per hour. The third scenario is the heavy rainfall scenario, which includes all traffic flow intervals with precipitation intensities higher than 1 millimetre per hour. Analysis on the effect of snow on motorway capacity could not be carried due to the limited days with snow within the examined years (2007, 2008 and 2009) and the absence of location specific snowfall data. A cumulative normal distribution function is fitted to the resulting data in order to arrive at a complete capacity distribution function. The comparison of the capacity is made based on the median value of the capacity distribution functions. Since it is the median value in a normal cumulative probability function, along with it is the traffic intensity value with the highest probability to occur and therefore the most representative capacity value. The results can be found in Table 1.

Table 1 - Comparison of the median capacity values in the different scenarios

			Dry		**Light rain**		**Heavy rain**	
motorway	Location pre-bottleneck (hm)	location post-bottleneck (hm)	Median capacity Free flow conditions (veh/h)	Median capacity Congested conditions (veh/h)	Free flow difference (%)	Congested difference (%)	Freeflow difference (%)	Congested difference (%)
A4R-2007	30.0	31.0	4452	3612	-4.2%	-6.6%	-10.3%	-5.3%
A4R-2008	30.0	31.0	4426	3624	-6.3%	-5.0%	-10.8%	-7.0%
A4L-2007	23.5	21.5	4368	3816	-3.9%	-4.1%		
A12R-2007	35.5	37.1	7173	5628			-7.3%	-5.1%
A12R-2008	68.1	68.7	4690	3864	-4.1%	-6.2%		
A15L1-2008	59.5	58.1	7267	6240	-4.4%	-6.9%		
A15L2-2007	80.9	80.1	4351	3768			-9.5%	-8.3%
A15L2-2008	80.9	80.1	4117	3792			-9.9%	-8.5%
A20R1-2007	31.0	31.9	6072	5460	-5.8%	-3.7%		
A20R1-2008	31.0	31.9	5939	5484			-7.5%	-7.7%
A20R2-2009	43.0	44.9	4205	3432			-11.0%	-4.2%
A20L-2007	32.2	31.2	6060	5268			-3.8%	-6.2%
A20L-2008	32.2	31.2	6064	5292			-3.7%	-6.3%
A20L-2009	32.2	31.2	6121	5388			-6.0%	-5.8%
A27L-2007	35.4	34.7	3938	3624			-6.1%	-5.0%
A27L-2008	35.4	34.7	3931	3624	-7.7%	-5.0%		
A50R-2007	156.3	157.5	4224	3516			-11.1%	-6.1%
A50L-2007	153.5	150.9	4181	3732	-8.9%	-7.1%	-8.1%	-9.0%
Average					-5.7%	-5.6%	-8.1%	-6.5%
Standard deviation					1.9%	1.3%	2.6%	1.5%

Light rainfall results in an average capacity reduction of 5.7% compared to dry weather. The capacity reduction if the results from different bottleneck locations are analysed, with the capacity reductions ranging from 3.9% to 8.9%. It is interesting to note that heavy rainfall, on an average, leads to a higher capacity reduction than light rainfall for free flow capacity, which is in accordance with expectations. There is a significant difference, but the average difference in reduction is not extremely high between light and heavy rain (5.7% vs. 8.1%) when one considers the fact that light rain only includes observations with rain intensities less than 1mm/hour and heavy rain includes all observations equal or higher than 1mm/hour. The difference in capacity between dry conditions and light rain is relatively large compared to the difference in capacity between light rain and heavy rain.

Observations of the capacity reductions for the same scenario at the same location lead to the conclusion that the capacity reduction at a bottleneck location is very robust and does not change a lot over the years. Taking into account the small difference between observations at the same location, it can be concluded that the large difference between observations at different locations (between -3.7% and 11.1%) is related to the different infrastructural characteristics at the different locations. A plausible conclusion is that the different motorway characteristics lead to the effect of heavy rainfall on motorway capacity being different at those locations. The road surface at the different locations might be an important factor in the reduction of motorway capacity. It could be the case that the capacity reduction is smaller on motorway sections with porous asphalt. This is in accordance with the study of Cools et al. (2007) on the effect of rain on different locations, which concluded the existence of heterogeneity in the effect of rain on different traffic count locations and the homogeneity of the rain effects on the upstream and downstream of a certain location. Comparing the results obtained in the analysis with findings from other studies leads to the conclusion that most other researchers have found capacity reductions which are within the same range as that of this study, leading to an increase in confidence concerning the results of this study.

3.2 The estimated motorway travel demand model

The estimated parameters of both utilitarian and recreational trips panel mixed logit models are presented in Table 2. As discussed before, all parameters are estimated alternative specific, hence, per model the table shows five sets of parameters. The alternative 'not making a trip' served as a reference alternative and therefore has utility of zero by definition. If an ASC (alternative specific constant) is not listed, this means that the coefficient is not statistically significant. The presented SIGMA's are the estimated standard deviations of the normally distributed ASC.

Table 2 - Results of the estimated Panel Mixed Logit models

	Utilitarian trip analysis			**Recreational trip analysis**	
	coefficient	t-value		Coefficient	t-value
Motorway			***Motorway***		
snow alarm	-0.57	-2.63	ASC	-2.01	-7.24
icy roads alarm	-0.82	-4.05	icy roads alarm	-1.19	-5.23
light rain	2.20	6.61	light rain	1.74	5.14
light snow	-1.23	-6.63	very heavy rain	0.49	2.11
heavy snow	-2.77	-12.49	heavy snow	-2.24	-8.28
motorway car group	4.69	16.77	motorway car group	2.23	7.81
public transport group	-3.89	-4.75	SIGMA	-2.38	-9.14
SIGMA	-3.61	-12.92			

Avoid morning peak			***Avoid morning peak***		
heavy snow	-0.88	-3.68	ASC	-0.78	-5.10
SIGMA	-1.29	-6.68	worse forecast	-0.56	-3.08
			better forecast	0.61	3.55
			light rain	0.90	3.05
			heavy snow	-1.36	-5.85
			SIGMA	1.15	9.50
Avoid motorway			***Avoid motorway***		
rain alarm	0.55	2.62	ASC	-2.99	-8.03
icy roads alarm	-1.23	-3.74	icy roads alarm	-0.71	-2.92
light rain	1.35	3.33	light rain	1.08	3.42
heavy snow	-2.43	-7.93	light snow	-1.47	-4.40
non-motorway car group	3.97	16.95	heavy snow	-1.79	-6.31
public transport group	-5.82	-4.76	motorway car group	-2.48	-6.69
SIGMA	-4.30	-11.76	non-motorway car group	2.79	6.59
			SIGMA	3.78	7.86
Bicycle			***Bicycle***		
alarm3	-1.50	-4.10	ASC	-2.72	-7.33
light rain	2.24	4.22	snow alarm	-1.60	-4.06
very heavy rain	-2.31	-3.7	light rain	1.05	2.96
light snow	-1.10	-2.87	light snow	-0.72	-2.27
heavy snow	-2.84	-4.95	heavy snow	-2.07	-4.50
motorway car group	-6.99	-7.02	motorway car group	-1.78	-6.77
motorway car very heavy rainfall	-3.53	-3.57	motorway car very heavy rainfall	1.24	4.24
public transport very heavy rainfall	2.21	3.53	SIGMA	-2.35	-11.99
SIGMA	-3.58	-7.09			
Public transport			***Public transport***		
light rain	1.13	3.05	ASC	-9.33	-4.31
heavy snow	-1.09	-3.46	SIGMA	-5.23	-5.26
motorway car group	-4.18	-8.00			
non-motorway car group	-1.66	-3.34			
public transport group	6.90	9.24			
public transport heavy snowfall	-1.08	-2.73			
SIGMA	3.06	9.29			
Not making a trip			***Not making a trip***		
ASC	0.00	reference	ASC	0.00	reference
Log-likelihood	-1386.50			-1348.86	
Rho-square	0.714			0.430	

We continue by discussing the main findings, starting with the utilitarian trips. The results indicate that the *weather forecast* does not have an influence on the travel behaviour for utilitarian trips. The *current weather* and a *weather alarm*, on the other hand, have significant effects on the adaptation of travel behaviour. *Rainfall*, however, does not have a significant effect on trip generation as suggested by the results for the alternative 'avoid morning peak'. *Heavy snowfall*, on the other hand, results in an increase in the probability of not making the trip. Furthermore, the results suggest that mode choice changes do not often occur a result of the weather. There is a very small change in the cyclists group towards the usage of the car, but this effect can be considered marginal. Route choice changes for car users resulting from weather conditions are also limited. Travellers that normally use the motorway will not change their route and will avoid the motorway in case of severe weather conditions. Also, changing the route is not very common for non-motorway travellers. Departure time changes only occur if there is a weather alarm. Overall, it can be concluded that the effect of weather conditions on departure time change is limited. The main decision that utilitarian travellers make is whether to stay at home or make their normal trip. The influence of the weather conditions on recreational trips is slightly different from the utilitarian trips. Weather forecasts play a smaller role in the choice to avoid the morning peak. It leads to a positive approach to avoiding the morning peak when travellers know that the weather is going to improve. Both the current weather and the weather alarm influence adaptation of travel behaviour more effectively for recreational trips compared to utilitarian trips. Trip generation of recreational trips is a significantly influenced by adverse weather conditions. Heavy rainfall leads to relatively high probabilities of not performing a trip. Heavy snow combined with a snow or icy roads alarm even leads to probabilities of 67.4% to 80.4% of not making the trip. Mode choice changes for recreational trips occur more than for utilitarian trips. In the rain scenario there is a significant modal shift from bicycle towards car. Route choice changes for recreational trips are similar to those for utilitarian trips. There is however a relatively high route choice change (up to 22.3%) for the non-motorway users group in case of heavy rain. The departure time is changed more often in comparison to utilitarian trips. Overall, the alternative 'avoid morning peak period' is preferred by recreational trip travellers. A possible explanation for this is (to some extent) the more flexible nature of the recreational trips as compared to utilitarian trips. Based on the model estimated, it can be predicted that as a result of the behavioural travel adaptation of travellers, the motorway traffic demand increases by 2.3% with light rainfall compared to dry weather, while demand decreases: by 2.3% in case of heavy rainfall scenario; by 7.7% in case of very heavy rainfall, by 22.2% in case of light snowfall, and by 29.4% in case of heavy snowfall. Furthermore, the addition of a weather alarm reduces demand travel demand by 19.4% in case of heavy rain and a rain alarm, by 48.8% in case of heavy snow and a snow alarm, and by 52.4% in case of heavy snow in combination with an icy roads alarm results compared to dry weather.

3.3 Effect of precipitation on breakdown probability

A generic model is developed that provides information regarding the breakdown probability of traffic on all Dutch motorways. Input that is necessary to arrive at the breakdown probability is the median capacity value and the traffic flow in the different precipitation scenarios. The difference in traffic flow relating to one standard deviation in breakdown probability is computed for all bottleneck situations and scenarios, and the average of these values is taken. This results in corresponding traffic flow changes at one standard deviation of 8.6% for dry weather, 7.0% for light rainfall and 7.4% for heavy rainfall. Due to the different standard deviations for the different rain scenarios, one function and plot is made for each of the scenarios, which can be seen in Figure 2a-c. With the development of the three generic models, breakdown probabilities can be calculated for any given traffic demand and median capacity. When the median capacity value of a certain bottleneck and the traffic demand are known, the intersection of this point with the function leads to the breakdown probability value. The resulting breakdown probability in the dry scenario can be used as a reference value. Inserting the adjusted traffic flow (reference traffic flow with the demand change) and the reduced median capacity into the model leads to a probability of breakdown in that scenario for that specific motorway.

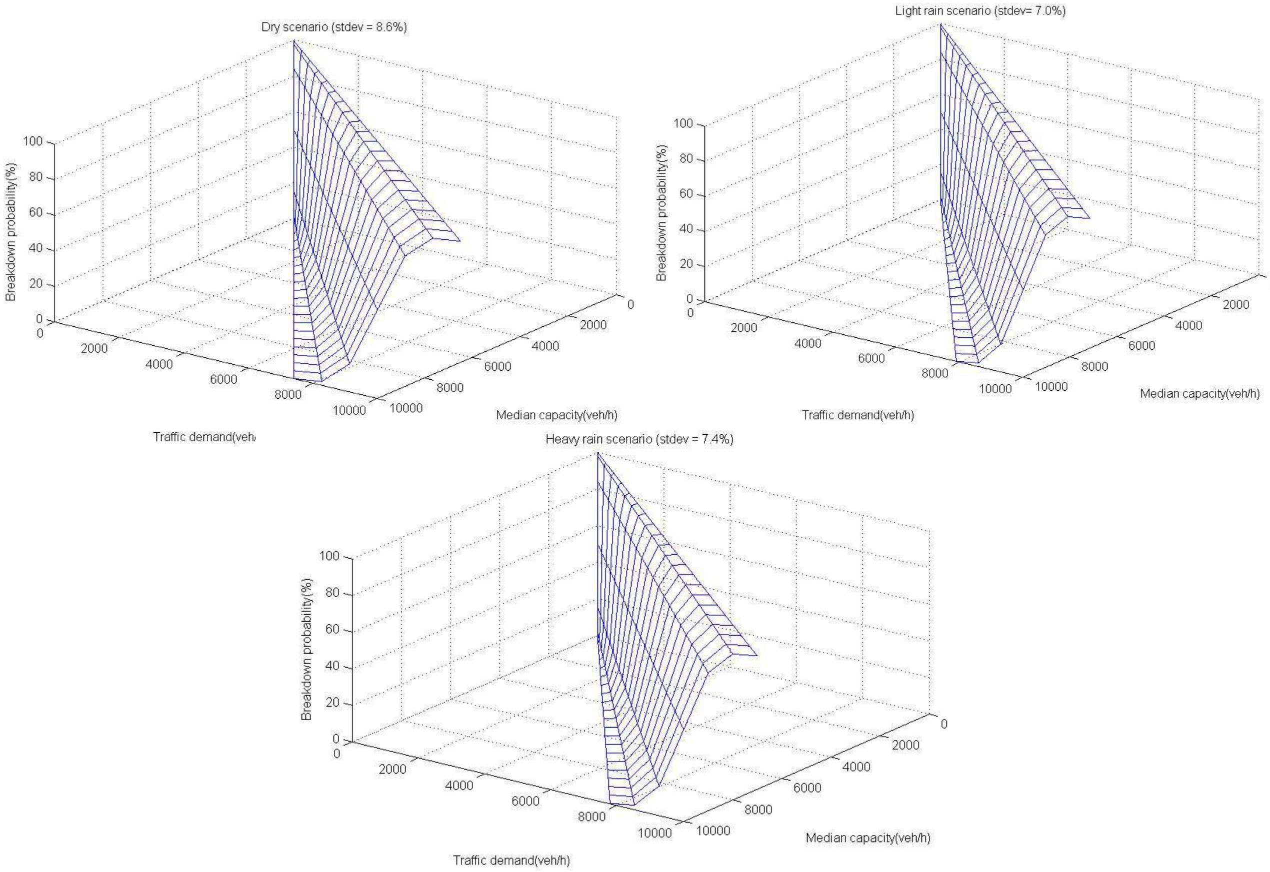

Figure 2a-c 3D-plot breakdown probability dry scenario (a), light rain scenario (b) & heavy rain scenario (c)

The traffic flow corresponding to the median capacity is used as a reference value. If the traffic flow is equal to the median capacity, this results in a breakdown probability of 50%. The traffic demand changes of +2.3% for light rain and -2.3% result in the traffic flow values per bottleneck location in these scenarios. The median capacity values for the bottleneck locations in the different scenarios are also presented. Furthermore, the average breakdown probability increases from 50% to 86.7% due to light rain. This is the result of the decreased capacity and an increasing traffic demand in this scenario. The range of breakdown probabilities for the different locations is between 81.7% and 94.6%, which can be explained by the different capacity reductions for the bottleneck locations. In the heavy rain scenario the average breakdown probability increases from 50% to 77.4%. The average probability of breakdown is lower than in the light rain scenario, while the average capacity reduction in the heavy rain scenario is larger than in the light rain scenario. This is the result of the decreased traffic demand in the heavy rain scenario.

4. Conclusions

This paper reports on a unique study that incorporates both the motorway traffic demand change and the motorway capacity reduction in the estimation of the congestion probability as a result of adverse weather conditions. A stated adaptation experiment was conducted and a Panel Mixed Logit model is estimated to arrive at a motorway traffic demand as a result of adverse weather. To examine the influence of precipitation on motorway capacity, distribution functions were estimated for dry weather, light rain and heavy rain based on the Product Limit Method. With the development of a generic model based on a cumulative normal distribution, breakdown probabilities can be calculated for any given traffic demand and capacity.

Capacity reductions at single bottleneck locations are very robust and do not change significantly over the years. A plausible explanation is that different motorway characteristics cause these differences. The road surface at the different locations may be an important factor in the reduction of motorway capacity. Future research needs to examine the effects of different road surfaces, to allow road authorities to select appropriate road surfaces at the bottleneck locations to limit reduces capacity reduction.

An important result of the stated adaptation experiment is that the motorway traffic demand increases by 2.3% with light rainfall and decreases by 2.3% in the heavy rainfall scenario as a result of the behavioural adaptation of travellers. The relatively small influence of rain on motorway traffic demand in the morning peak significantly influences the breakdown probability on motorways. An increase in demand of only 2.3% could lead to an increase in breakdown probability of 11 percentage points at a bottleneck location. Combining both the traffic demand change and the capacity reduction leads to the conclusion that rainfall leads to a significant increase in the probability of traffic breakdown at bottleneck locations. A breakdown probability of 50% in dry weather leads to an average breakdown probability of 86.7% in light rain and 77.4% in heavy rain conditions. The higher breakdown probability in light rainfall is the result of the increased traffic demand.

It can be concluded from this study that both traffic demand and motorway capacity should always be incorporated in the analysis to arrive at accurate predictions regarding breakdown probabilities. The results regarding the different increases in breakdown probability at different locations as a result of precipitation can be taken into account by road authorities in the decision to assign budgets to motorway improvement projects. Investing in the bottleneck locations at which rain leads to the biggest increase in breakdown probability could be more interesting. This may increase the probability that the goals of congestion reduction set by policy makers will be met.

5. Discussion

The results obtained regarding the demand changes in this research have three limitations. Firstly, the results are based on stated behaviour instead of revealed behaviour. As common for stated research, stated behaviour may differ from actual behaviour, moreover, the hypothetical weather situations may be differently interpreted by respondents. Secondly, the results of the travel behaviour analysis are average changes in motorway traffic demand. With the high importance of small changes in travel demand, investigating the effect of location specific rainfall on the motorway traffic demand should be considered. Thirdly, there was no data available of the number of travellers in the different travel groups (car motorway, car non-motorway, public transport and bicycle). In this study the importance of the groups was based on the number of respondents of the groups in the sample. Data regarding the division of the groups in the population could have increased the accuracy of the traffic demand predictions.

Acknowledgements

The author would like to thank TNO for funding of the research project.

References

Al Hassan, Y., & Barker, D. (1999). The impact of unseasonable or extreme weather on traffic activity within Lothian region, Scotland. *Journal of Transport Geography*, 209-213.

Ben-Akiva, M., & Lerman, S. (1985). *Discrete choice analysis: Theory and application to travel demand.* Cambridge: MIT Press.

Bierlaire, M. (2003). BIOGEME: A free package for the estimation of discrete choice models. *Proceedings of the 3rd Swiss Transportation Research Conference.* Ascona, Switzerland.

Bierlaire, M. (2011, June 2011). *p-values are highly insignificant yet rob. p-values highly significant*. Retrieved April 24, 2013, tech.groups.yahoo.com/group/biogeme/message/1751

Böcker, L., Dijst, M., & Prillwitz, J. (2012). Impact of Everyday Weather on Individual Daily Travel Behaviours in Perspective: A Literature Review. *Transport Reviews: A Transnational Transdisciplinary Journal*, 1-21.

Brilon, W., Geistefeldt, J., & Regler, M. (2005). Reliability of freeway traffic flow: A stochastic concept of capacity. *Proceedings of the 16th international symposium on transportation and traffic theory.* College Park, Maryland.

Call, D. (2011). The effect of snow on traffic counts in western New York State. *Weather Climate and Society*, 71-75.

Calvert, S., & Snelder, M. (2013). Influence of rain on motorway road capacity – a data-driven analysis. *Proc. of ITSC 2013, IEEE 16th International Conference on Intelligent Transportation Systems.* The Hague, september 2013.

Chung, K., Rudjanakanoknad, J., & Cassidy, M. (2007). Relation between traffic density and capacity drop at three freeway bottlenecks. *Transportation Research Part B: Methodological, 41*(1), 82-95.

Cools, M., Moons, E., & Wets, G. (2007). *Assessing the impact of weather on traffic intensity.* Hasselt: Hasselt University.

Elefteriadou, L., Roess, R., & McShane, W. (1995). Probabilistic nature of breakdown at freeway merge junctions. *Transportation Research Record* (2027).

Kaplan, E., & Meier, P. (1958). Nonparametric estimation from incomplete observations. *Journal of the American Statistical Association, 53*, 457-481.

KNMI. (2011, November 14). *Nader verklaard: Weeralarm (code rood)*. Retrieved January 18, 2013, from http://www.knmi.nl/cms/content/75937/weeralarm_code_rood

Lorenz, M., & Elefteriadou, L. (2001). Defining freeway capacity as function of breakdown probability. *Transportation Research Record 1776*, 43-51.

Minderhoud, M., Botma, H., & Bovy, P. (1997). Roadway capacity estimation methods explained and assesed. *Transportation Research Record 1572*, 59-67.

Molin, E., van Stralen, W., & van Wee, G. (2012). Car drivers' preferences for electric cars. *91th Annual Meeting of the Transportation Research Board.* Washington.

Persaud, B., Yagar, S., & Brownlee, R. (1998). Exploration of the breakdown phenomenon in freeway traffic. *Transportation Research Record*(1634).

Regler, M. (2004). *Verkehrsablauf und Kapazitaet auf Autobahnen (Freeway Traffic Flow and Capacity).* Bochum: Ruhr-University Bochum.

Sabir, M. (2011). *Weather and travel behaviour.* Amsterdam: VU University.

TNO. (2011). *Top 15 filelocaties voor verschillende fileoorzaken in Nederland.* Delft: TNO.

Toorenburg, J. v. (1986). *Praktijkwaarden voor de capaciteit. .* Rotterdam: Rijkswaterstaat dienst verkeerskunde.

Zurlinden, H. (2003). *Ganzjahresanalyse des Verkehrsflusses auf Strassen (Whole-Year-Analysis of Highway Traffic).* Bochum: Ruhr-University Bochum.